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2302 M1G2

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO) 07 Sep 2001

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-AB-2001-184**
C.T. Liu, "Fracture Mechanics and Service Life Prediction Research"

AFOSR Program Review **(Statement A)**
Washington, D.C., 18-20 Oct 2001) (Deadline: 28 Sep 2001)

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PHILIP A. KESSEL Date
Technical Advisor
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FRACTURE MECHANICS AND SERVICE LIFE PREDICTION RESEARCH

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suggest capitalizing the "E" suggest adding a colon here

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Narrative Description of the program:

The goal of this program is to develop a basis for developing advanced crack growth and service life prediction technologies for predicting the service life of solid rocket motors. The objectives of this program are to (1) gain a fundamental understanding of fracture and crack growth behavior in solid rocket motors; (2) investigate the effects of damage, material nonlinearity, pressure, and loading rate on crack growth behavior in a solid propellant; (3) simulate crack growth behavior and gain insight for improving crack growth resistance in solid propellant; and (4) determine the crack growth behavior of an interfacial crack in bimaterial bond systems. The main issues in service life prediction of solid rocket motors are the lack of a fundamental understanding of crack growth behavior under service loading conditions and a reliable methodology to predict crack growth. The main technical challenges are microstructure effects on damage initiation and evolution, large and time dependent deformation, short crack and stress raiser interaction, and multi-layer structures with time-dependent material properties and property gradients. The program's basic approach involves a blend of analytical and experimental studies. In general, mechanisms and mechanics involved in cohesive fracture in a solid propellant and adhesive fracture in bond systems are emphasized. In this program, nonlinear viscoelasticity, fracture mechanics, experimental mechanics, damage mechanics, nondestructive testing and evaluation, and numerical modeling techniques will be used.

- pls hyphenate this word

These research studies address a number of important subjects such as cumulative damage and crack growth behavior in solid propellants, statistical nature of crack growth, and bonded interface failure. The results of these studies have the potential of becoming some of the most significant contributions to the rocket industry and research community.

Detailed Technical Approach for Next Fiscal Year:

In FY 01 there are four major tasks: Task 1- investigating the effects of pressure, strain rate, and damage on short crack growth behavior in a solid propellant, Task 2 - determining the validity of using linear fracture mechanics to characterize the crack growth behavior in a solid propellant, Task 3 - including pressure effect in numerical modeling of crack growth, and Task 4 - determining the strain rate effects on the constitutive behavior as well as on the local damage and deformation near the tip of interfacial cracks of a propellant/liner/propellant bond system.

Task 1: Investigating the Effects of Pressure, Strain Rate, and Damage on Crack growth Behavior in a Solid Propellant

Pls try - keep this heading with its corresponding paragraph(s).

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In Task 1, experiments were conducted on uniaxial specimen with two different initial crack lengths (0.1 in. and 0.3 in.) at four different displacement rates (0.2in/min, 2 in/min, 50 in/min, and 200 in/min) under three confined pressures (ambient, 500 psi, and 1000 psi). Preliminary results of data analysis revealed that cracks grew slow under confined pressure. The decrease in crack growth rate under confined pressure is due to the suppression of the development of damage in the material and the decrease in strain gradient near the crack tip (Fig.1). At the time of this writing, the basic damage mechanisms, including damage initiation and evolution, under multiaxial (constant strain rate and confined pressure condition) is not clear. In order to provide a fundamental understanding of the effects of multiaxial loadings on crack growth behavior additional studies, including experiments and numerical modeling, will be conducted in FY 02.

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During FY 01, in addition to experimental study on the effect of confined pressure on crack growth behavior, research was centered on the development of a rate-independent constitutive model, including the pressure effect. Particularly, the study was conducted on modeling the effect of hydrostatic pressure on the progressive damage. In order to model the effect of hydrostatic pressure on the damage, the damage theory previously developed was modified, and it was included in the constitutive model. Also, the technique developed previously, called the multi-scale approach, was used along with the damage theory at the matrix material level. The multi-scale approach is based on the interconnection between the micro level (i.e.particle and matrix material level) and the macro level (i.e.the particulate composite level), and it was used to predict the stress-strain behavior of the material under ambient pressure and 1000 psi confined pressure conditions. An excellent agreement exists between the predicted and the experimental stress-strain curves (Fig.2).

Pls add commas after "i.e." — Pls add a space

Task 2: Crack Instability and Growth Models

Sub-Task 1: Instability Criteria for Short Crack Growth

In this task, the instability criteria for the onset of growth of short cracks will be developed. Based on last year's study, we found that for short cracks, defined as the crack length is equal or less than 0.1 in., classic fracture mechanics cannot be used to determine the critical condition for the onset of crack growth. In FY 01, a linear fracture mechanics solution was modified to predict the behavior of short cracks. An effective crack length was introduced into the Mode I stress intensity factor. By using the effective crack length, a reasonably good agreement exists between the fracture toughnesses for the onset of growth of short and long cracks. Additional work will be conducted in FY02 to develop the instability criterion for the onset of growth of short cracks, based on continuum and fracture mechanics theories.

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Sub-Task 2: Nonlinear Crack Growth Model

In this task, nonlinear and linear fracture mechanics together with numerical modeling techniques will be used to determine the capability of using linear fracture mechanics to characterize the crack growth behavior in a solid propellant under confined pressure. According to the previous studies, under ambient pressure, the crack grew rapidly when the specimen was deformed beyond the point of maximum tensile stress. However, based on recent experimental observation, it was noted that, under suggest adding "observed" here

confined pressure, a considerable amount of stable crack growth took place when the specimen was deformed beyond the maximum applied stress. This type of crack growth behavior is significantly different from that under ambient pressure. Therefore, in order to predict the criticality of a crack in a solid rocket motor under a pressurization condition, a nonlinear fracture mechanics theory is needed to characterize the crack growth behavior and to develop a crack growth model. In FY 02, efforts will be centered on nonlinear analysis of crack growth behavior and determining the applicability of using linear fracture mechanics to characterize the crack growth behavior under confined pressure.

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Sub-Task3: Determining the Representative Volume for the Validity of Homogeneous Continuum Assumption of the Material. - delete the period

In FY 00, real-time x-ray techniques were used to investigate the validity of the homogeneous continuum assumption of the solid propellant. The real-time x-ray test data indicated that the particles were randomly distributed in the particulate composite material. When the size of an area becomes larger than 2 mm x 2 mm, the microstructure becomes statistically uniform. In other words, the area size of 2 mm x 2 mm is about the smallest to represent the average smeared behavior of the composite. This 2 mm x 2 mm area is defined as a representative area. In FY 01, Lockheed-Martin Research Laboratory's Computed Tomography system was used to determine the representative volume of the material. Preliminary data showed that the representative volume of the material is 2 mm x 2 mm x 2 mm. (Fig. 3). This information can be used to correlate the material property to nondestructive testing parameters, providing a basis for conducting stress analysis of structures from nondestructive testing data. In FY 02, the Computed Tomography System will be used to monitor damage initiation and evolution processes inside the specimen under incremental strain conditions and to correlate microstructure to surface strain measured on the specimen surface.

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Sub-Task 4: Investigating the Effect of Strain Rate on the Critical Initial Crack Length in the Material

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In FY00, a technique was developed, based on fracture mechanics and probabilistic mechanics, to predict the critical initial crack size, which is responsible for the fracture of the specimen. In FY 01, the developed technique was modified to include rate effect. The modified technique can be used to predict the initial critical crack size at different strain rates with good accuracy. For example, at 18.182 in/in/min strain rate, the predicted and the measured initial critical crack size are 0.146 in and 0.12 in, respectively. The results also show that the critical initial crack size is insensitive to strain rate. For example, at 0.067 in/in/min and 0.727 in/in/min strain rates the predicted initial critical crack size are 0.13 in and 0.119 in, respectively. The determination of the initial critical crack size and its statistical distribution function will make statistical and reliability analyses of crack growth feasible.

Pls add a "s"

Pls add periods to abbreviate inches -

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- Did you mean to say "predicted and measured" or just "predicted" initial crack sizes?

Task 3: Numerical Modeling of Time-Dependent Crack Growth Behavior. - delete the period

In this task, a nonlinear viscoelastic constitutive model was incorporated into a finite element code (FEAP), which was used to model the crack growth behavior in a solid propellant. The response of the undamaged material is assumed to be governed by a homogenized linear viscoelastic constitutive relation. The bulk and the shear moduli of the material are assumed to undergo degradation with accumulation of damage. The critical damage parameter is taken to be the maximum volume dilatation accumulated in the material. In the finite element analysis, the crack propagation is simulated by using a node release technique after having attained a critical level of dilatation in the

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elements. In FY01, the effect of pressure on the constitutive behavior was included in the constitutive model, which was incorporated in the FEAP computer program. In FY 02, the accuracy of the computer program will be determined by comparing the numerically predicted and experimentally measured crack growth behavior.

Task 4: Interfacial Fracture of Bimaterial Bond Systems

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Sub-Task 1.Photoelastic Analysis of Three-Dimensional Effects of Cracking of Motor Grain Geometries under Internal Pressure loads. - Pls capitalize the "l"

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In FY 01, a series of experiments on photoelastic scale models of motor grain were conducted using the frozen stress method. The results of preliminary data analysis revealed that symmetric cracks penetrated to the outer surface of the model before the off-axis cracks had grown significantly. Data also revealed a shear mode along with Mode I in the off-axis cracks before they were completely turned (Fig.4). In FY02, a detailed analysis will be conducted to determine the three-dimensional effects on the stress distribution at various locations along the crack front.

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Sub-Task 2: Deformation and Failure Mechanism of Propellant/Liner/Propellant Bonded Specimens

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do not capitalize the "A" – In FY01, A series of experiments on propellant/liner/propellant bonded specimens were conducted at 0.01 in/min displacement rate. A computer aided speckle interferometry technique was used to determine the displacement and strain distributions in the specimen. Two interface debonding modes, debonding from the center and the corner of the interface of the specimen, were observed. These debonding modes appeared to be related to the specimen geometry. In addition, the strain rate in the interphase and liner layers increase with increasing time and are significantly different from the constant applied strain rate (Fig.5). In FY 02, the effect of the applied strain rate and interfacial strength on the deformation and strain distributions in the bonded specimen will be investigated.

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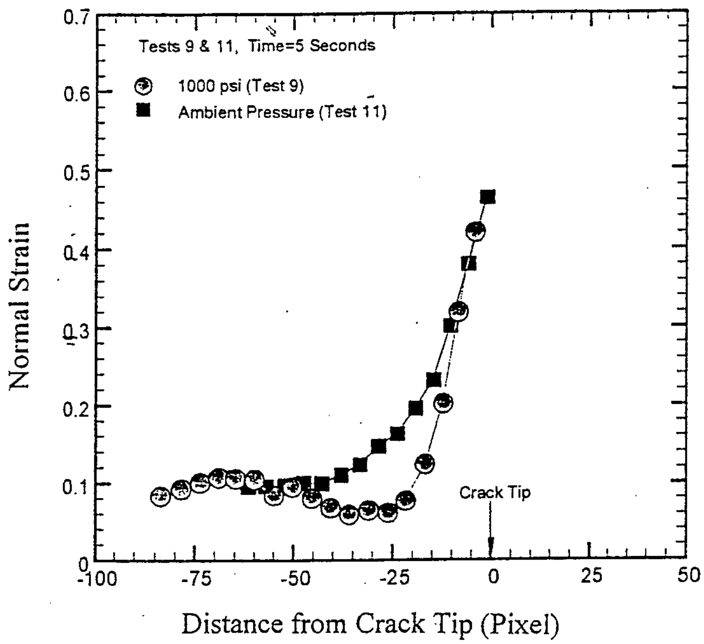
Sub-Task 3: Numerical modeling of the Propellant/Liner/Propellant Bonded specimen. - delete the period

In this sub-task, numerical modeling analysis, based on an elastic-plastic analysis, of the propellant/liner/propellant bonded specimen will be conducted. The information obtained from the numerical analysis will be used to explain the phenomena observed from experiments. At the time of this writing, a finite element model was developed and a detailed analysis was started.



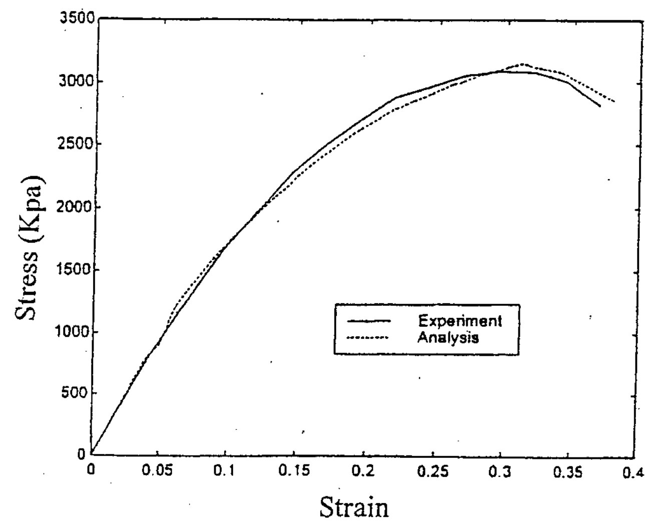


Fig. 1 Normal Strain Vs Distance from Crack Tip

Fig. 2 Comparison of Stress-Strain Curves with Hydrostatic Pressure (1000 psi)

Suggest "vs." - lowercase "v" and a period after the "s"

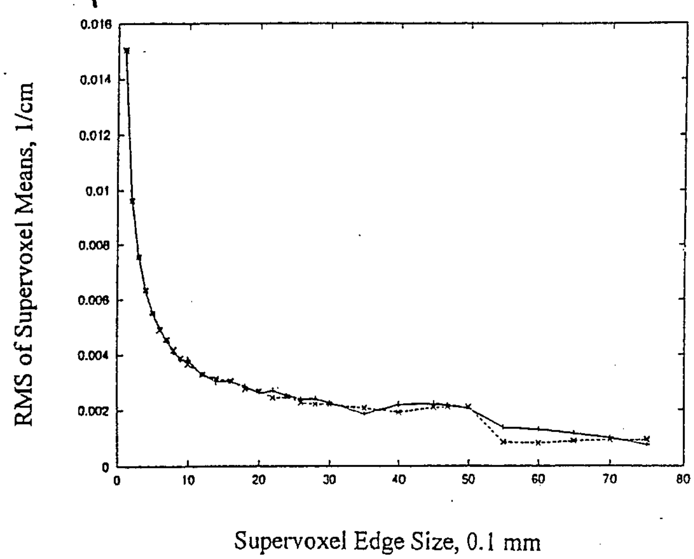


Fig.3 RMS of Supervoxel Mean Vs Supervoxel Volume

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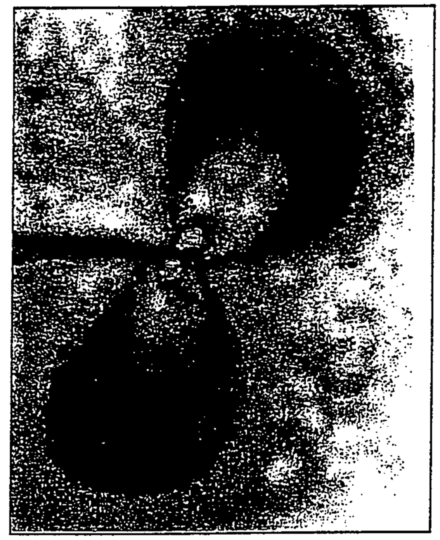
See comment for Fig. 1

(a) Crack Turn Complete



(b) Crack Turn Incomplete

Fig.4 Photoelastic Fringe Patterns

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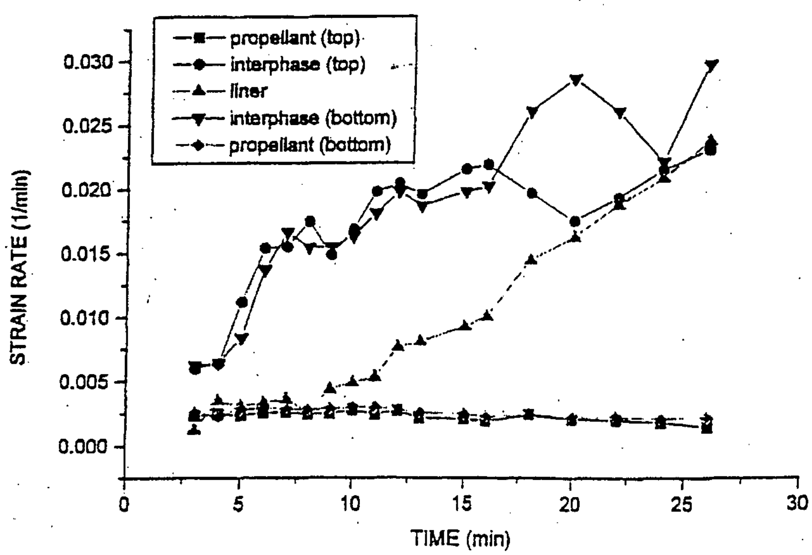

Fig.5 Strain Rates of Different Regions Vs Time

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see comment for Fig. 1